

**June 14, 2007**  
**Dr. Jane C. S. Long**  
**Associate Director for Energy and Environment**  
**Lawrence Livermore National Laboratory**  
**“Testimony before the US-China Economic and Security Review Commission”**  
**For**  
**China’s Energy Consumption and Opportunities for U.S.–China Cooperation to Address the**  
**Effects of China’s Energy Use**  
*With Julio Friedmann, Philip Cameron-Smith, Gerald Potter, Cynthia Atherton, and Julie Lundquist*

I am Jane C. S. Long, the Associate Director of Energy and Environment for the Lawrence Livermore National Laboratory (LLNL) in California. Thank you for the opportunity to testify. My remarks will focus on the need for the US to continue to collaborate with China on climate research, the need to pursue research on aerosol transport and emission verification to better understand the global effects of pollutants, and the need for the US to develop joint projects with China on wind energy, carbon sequestration and in situ coal gasification.

LLNL is a national security laboratory with about 8,000 employees. Its capabilities in climate science and energy stem from strong research programs in atmospheric and earth sciences, which grew out of earlier nuclear testing activities. When above-ground nuclear tests stopped, LLNL’s atmospheric science program continued to flourish and address concerns about stratospheric ozone depletion, potential effects of nuclear winter in the 1980s, and consequences of accidental airborne release of harmful substances. It is now an internationally recognized climate and atmospheric science program with approximately 50 scientists. Underground nuclear testing required the Laboratory to have a strong Earth science program, which subsequently has studied many issues related to containment of waste and subsurface resource extraction. LLNL also has exceptional scientific computing capabilities, including the world’s fastest computer, BlueGene/L.

**I. A Perspective on the Global Energy Future and its Effect on Research Priorities**

The global energy future is affected by three key factors: climate change, economics, and energy security. There is scientific consensus that greenhouse gases, primarily from burning fossil fuels for energy, are creating rapid climate change with potentially catastrophic consequences. Adequate energy capacity and supply are needed; otherwise economic vitality could be strangled by high prices for energy. Energy security is concerned with the geo-politics of oil and our nearly exclusive use of this fuel for transportation. This factor drives energy choices to end our “addiction to foreign oil” and use domestic sources of energy to create “energy independence.”

The energy system we have now is dominated by the economics factor. Fossil fuel is the least expensive alternative for energy, but its widespread use is responsible for concerns about the other two factors. If climate change dominates future choices, proposed solutions typically require financial subsidies, cause market inefficiencies, and lead to higher prices. If energy security dominates considerations, proposed solutions typically either have little effect on the climate problem (corn-based ethanol) or worse, increase our greenhouse gas emissions significantly (coal-to-liquids without carbon sequestration).

Climate change can be expected to have profound effects on our world if we do not address greenhouse gas emissions. Vast populations in the developing world may find themselves without

homes, food, or water. Regions and peoples will become ripe for violence, and in this sense, climate change is a security concern. If carbon reduction is the clarifying central concept, work will focus on least-cost, effective solutions that collaterally address this security concern. Elements of this carbon-reduction strategy include lowering energy demand through efficiency, performing research to make renewable energy less costly, finding ways to best tap power from intermittent renewable sources, making carbon sequestration an economical option so that we can use coal with impunity, and positioning nuclear power as a reasonable alternative (and then run cars with energy from the electric sector). These steps will reduce dependence on oil imports and security risks due to climate change. Further, the pursuit of green energy will create whole new markets and may provide an economic stimulus for the first adopters. Clearly there is a critical role for technology development to create options for carbon-free energy. This analysis informs the Laboratory's research strategy.

Our research strategy is to address three key issues:

- (1) We need to understand what is happening to the climate and the environment.
- (2) We need to change the energy system to eliminate greenhouse gases.
- (3) We need to adapt to climate change already happening.

I will discuss issues (1) and (2) below in the context of your specific questions. Our work on issue (3) is focused largely on water. Climate change will reduce water supplies in many parts of the world while at the same time increasing demand for water. This need for water will create new demand for energy in order to purify water from other sources, and even more water will be needed for irrigation. The increased energy use could worsen climate change, thereby creating a self reinforcing process that might become very serious, particularly in South Asia. The Himalayan glaciers that supply water are melting and the use of coal for energy in this part of the world is growing very rapidly. The possibility of other self-reinforcing processes in this and other parts of the world deserves further examination.

## **II. Understanding Climate Change: Exchanges with China**

In 1985, the US Department of Energy (DOE) (specifically, the Biological and Environmental Research program within the Office of Science) and People's Republic of China representatives signed an agreement to carry out a joint research program on the study of global warming due to enhanced greenhouse effects. A number of US institutions were asked to participate, including LLNL. This effort was one of the first steps to help provide opportunities for atmospheric scientists in both countries to share climate information that would lead to a better understanding of the Earth's climate system and eventually, aid in regional climate predictions. Under the agreement over 200 joint publications have been prepared and several unique climate data sets have been developed. The agreement has been renewed several times, most recently in September 2006. LLNL scientists continue to play an important role in this joint study.

As a result of the first meeting between US and PRC scientists, several tasks of mutual interest were identified. They included: analysis of climate models (Task 1), preparation and analysis of historical climate data (Task 2), understanding the relationship between large-scale and regional climate (Task 3), and methane measurements (Task 4).

LLNL scientists, led by Dr. Gerald Potter, primarily worked on Task 1. This work eventually evolved into a model intercomparison project and was the progenitor of the present day Program for Climate Model Diagnosis and Intercomparison (PCMDI) at LLNL. PCMDI, which compares

and archives results from all the world's major climate models, has been the world's leader in the problem of detection and attribution of climate change. PCMDI provided the International Panel on Climate Change (IPCC) with 35 terabytes of data (about 3 ½ Libraries of Congress) to inform the 2007 report, which concluded with 90% certainty that global warming is influenced by anthropogenic activity.

In support of Task 1, several LLNL scientists have visited China and one Chinese scientist came to LLNL for an extended visit and published three papers in collaboration with LLNL scientists. Dr. Potter, in particular, has met with Chinese scientists as a member of the US delegation on a regular basis, most recently in September 2006. In general, the visits were to facilitate analysis and exchange ideas and model data generated by scientists at the Chinese Academy of Science Institute of Atmospheric Physics (IAP). Ideas and data have also been exchanged with the Chinese Meteorological Administration (CMA). These exchanges assisted Chinese investigators at the Institute of Atmospheric Physics (IAP) to configure their coupled ocean-atmosphere model for participation in the Coupled Model Intercomparison Project (CMIP), standardize their climate model data for use by others, efficiently analyze atmospheric data, and formulate numerical experiments to examine the sensitivity of simulating East Asian Climate with various regional climate models. As a result of the model intercomparison activities at LLNL's PCMDI, a new project was organized to analyze and understand the predictability of the East Asian Monsoon. Subsequent meetings in the PRC and Taiwan have helped improve our understanding of this phenomenon, which is so vital to agriculture in Asia.

### **III. Understanding the Environment: Trans-Pacific Transport of Aerosols**

LLNL has studied the long-range transport and reaction of key gases and aerosols for the better part of two decades. We first developed a global atmospheric chemistry-transport-model (called GRANTOUR) that was driven by meteorological fields from a general circulation model, NCAR's CCM1 (Community Climate Model, version 1). In the 1990s, we developed IMPACT, an improved global model that was driven by meteorology either from a general circulation model or actual assimilated meteorology. IMPACT contains a full suite of reactive chemistry models for the troposphere and stratosphere. Hence, it can predict the concentration of key greenhouse gases, including tropospheric O<sub>3</sub>, CH<sub>4</sub>, nitrous oxide (N<sub>2</sub>O), and fluorocarbons. IMPACT also predicts five aerosol species: sulfate, organic carbon, black carbon, dust, and seasalt.

The model has been used to study changes in the scattering of short-wavelength radiation due to increased fossil fuel sulfur emissions. It is also used to study carbon dioxide (CO<sub>2</sub>), an important greenhouse gas. By comparing IMPACT-predicted isotopic ratios of <sup>14</sup>C to <sup>12</sup>C to observations, one can determine the fossil-fuel contribution to CO<sub>2</sub> and the exchange rate of CO<sub>2</sub> between air and sea. This information helps scientists to better understand the carbon cycle.

A series of roughly 25 IMPACT simulations is being incorporated into the HTAP/LRTAP (Long Range Transboundary Air Pollution/Hemispheric Transport of Air Pollution) International Modeling Collaboration–Interim report to be published in 2007. The goal is to understand trans-Pacific and trans-Atlantic transport and reaction of a number of key gas and aerosol species. This is an important issue, and in internally-funded work, we have used IMPACT to study long range transport of aerosols from China to the United States. We found that measured aerosols at two clean-air sites in Northern California were totally dominated by Trans-Pacific transport (with the added surprise prediction that over 40% of the dust actually originated in Africa and the Middle East). Air-quality affects public health, and balancing the competing costs and benefits is

challenging. When the pollution is from a different country, the issue becomes much more complicated.

Our future studies will continue to assess the long-range transport, fate, and radiative effects of key chemically and climatically important gases and aerosols, including CH<sub>4</sub>, N<sub>2</sub>O, O<sub>3</sub>, CO<sub>2</sub>, black carbon, organic carbon, sulfate, dust, and sea salt. We will use the IMPACT model, and CAM3, a community atmospheric model that is part of the CCSM structure. Our modeling capabilities will allow us to assess the effect of changing energy emission strategies and greenhouse mitigation options on a number of important species.

#### **IV. Energy technology: Wind Energy**

China is considered to have tremendous wind resources: on the mainland, 235 GW practical wind energy potential has been estimated by the Chinese Academy of Meteorological Sciences, with up to three times that in the shallow waters off the eastern shore. However, as in the US, integrating this fluctuating source of renewable energy into a grid requires accurate predictions of wind variability. LLNL's expertise in numerical weather prediction (NWP) and our improvements to NWP models specifically for high-resolution simulations offer insight to enable this integration. These tremendous wind resources might change as global weather patterns change; LLNL's climate modeling expertise can suggest which areas of high wind resource will continue to be optimal for development in a changing climate.

#### **V. Energy Technology: Carbon Sequestration and Underground Coal Gasification**

In the US and world-wide, about 25% of the energy comes from coal, and coal accounts for about 40% of energy-related CO<sub>2</sub> emissions. Coal is responsible for a much larger proportion of Chinese emissions (81%). The Chinese use 59.6 quadrillion BTUs annually (2004 EIA data)—supplied by coal (69%), oil (22%), hydroelectric (6%), natural gas (3%), and nuclear (1%). The Chinese have built about 1000MW of coal fired electricity per week in the last year, so their CO<sub>2</sub> emissions are growing quickly and expected to pass those of the US shortly. China shares the same climate, economic, and energy security concerns that we have. As do Americans, the Chinese import much of their oil. EIA estimates that China's oil consumption increased by almost half a million barrels per day in 2006, or 38% of the total growth in world oil demand. China is the world's third-largest net importer of oil behind the United States and Japan, an important factor in world oil markets. Like the US, China has plentiful, cheap domestic coal supplies. Clearly, for both the US and China, controlling CO<sub>2</sub> emissions from coal is a priority.

Carbon capture and sequestration and in-situ coal gasification are the most important technology pathways that could help continue to meet energy needs while dramatically reducing the emission of greenhouse gases. Carbon capture and sequestration should be a vital element of a comprehensive energy strategy that includes efficiency gains, conservation, and carbon-free energy supplies such as renewable or nuclear power. They can also support environmentally sound development of domestic transportation fuels (including biofuels, coal-to-liquids, and hydrogen) and a smooth transition to a carbon-free energy infrastructure. In-situ coal gasification, also called underground coal gasification, would provide low-cost synthetic gas. By eliminating mining and reducing criteria pollutants and greenhouse gas emissions, the technology would be an environmentally preferred way to use coal resources.

***Carbon Capture and Sequestration (CCS).*** There are two components to CCS. The first is the separation and concentration of CO<sub>2</sub> from point source flue gases, which are produced at power

plants, refineries, ethanol plants, fertilizer plants, and other sources like cement factories. This step is needed to bring CO<sub>2</sub> concentrations up to 95% prior to the second step, sequestration. Geological carbon sequestration (GCS), or carbon storage, involves injecting CO<sub>2</sub> into porous rock formations deep below the surface. The goal is to keep CO<sub>2</sub> out of the atmosphere so as to avoid atmospheric warming and the consequences of climate change while allowing the continued use of fossil fuels for power generation and industrial purposes.

Over the past two years, much has been written on the subject of CCS. The IPCC 2005 special report includes a 135-page chapter on GCS. The MIT Report on the Future of Coal discusses geological sequestration in detail. Shortly, the National Petroleum Council will publish its 30 year strategy that includes a chapter on GCS. The DOE has just released its 2007 Technology Roadmap for carbon capture and sequestration. These documents and others I could cite serve as resources to those interested in learning more about CCS technical details.

Basically, geological carbon sequestration involves compressing CO<sub>2</sub> to elevated pressures and injecting it into geological formations that are from 3,000 to 20,000 feet deep. The most promising reservoirs are porous and permeable rock bodies, generally at 1 km depth and pressures and temperatures where CO<sub>2</sub> would be in a supercritical phase in which it behaves like a very dense, liquid-like gas. These potential reservoirs include:

- *Saline formations*, which contain brine in their pore volumes, commonly of salinities greater than 10,000 ppm.
- *Depleted oil and gas fields*, which have water and hydrocarbons in their pore volumes and a demonstrated seal. Injection of CO<sub>2</sub> into these reservoirs can stimulate enhanced oil recovery (EOR) or enhanced gas recovery and increase domestic fuel supply; substantial CO<sub>2</sub>-EOR already occurs in the US with both natural and anthropogenic CO<sub>2</sub>.
- *Deep coal seams*, often called unmineable coal seams, which comprise organic minerals with brines and gases in their pore and fracture volumes.

Once the CO<sub>2</sub> is injected into the subsurface, it will flow throughout the storage formation where it will remain trapped. This trapping will keep those greenhouse gases out of the atmosphere indefinitely. The IPCC issued a special report in 2005 on the topic of carbon sequestration, stating that if a site is well chosen well and well operated, then it is highly likely (>90% probability) to store 99.9% of injected CO<sub>2</sub> in place for hundreds of years, and likely to store 99% for thousands of years.

The US annually emits 2 billion tons CO<sub>2</sub> from large point sources, including about 1.5 billion tons from coal power generation, which accounts for 25% of US CO<sub>2</sub> emissions. The volume of this amount of CO<sub>2</sub> injected at depth exceeds current US oil and natural gas production combined. A single 1000 MW coal power plant will emit from 5 to 8 million tons CO<sub>2</sub> each year, roughly the same emissions as a 25,000 barrel/day coal-to-liquids plant. With sequestration in an appropriate geological formation, a 50 year injection program for one of these plants would accumulate in excess of 2 billion barrels of CO<sub>2</sub>.

While a challenge, it appears that the US has more than enough capacity to deploy CCS at large scale. Conservative estimates are that the US has 2,200 billion tons capacity. Large sequestration resources occur in the midwest, Texas, and the intermountain west. Substantial opportunities also exist in California, the Dakotas, Michigan, and offshore of the eastern US. The largest of these resources lie in saline formations and depleted oil and gas fields. While these published estimates

are uncertain, it is likely that they substantially underestimate total US capacity. Said another way, we appear to have enough capacity to inject all of our current point source CO<sub>2</sub> emissions for more than 100 years, and are likely to be able to do so comfortably for more than 1000 years.

DOE's carbon sequestration program plays a major role in US and global CCS research, development, and deployment. The program includes the proposed FutureGen plant, a 275 MW coal plant that gasifies coal, makes hydrogen and electricity, and integrates carbon capture and sequestration into its design. The FutureGen Alliance, which comprises 13 organizations including China's Huaneng Group, leads the project (<http://www.futuregenalliance.org/>). It is on-track to inject 1 million tons of CO<sub>2</sub> each year beginning 2012 (Mr. Michael Mudd, the President of the Alliance, will also testify in this hearing). In addition, DOE has created seven Regional Carbon Sequestration partnerships, which now cover 41 states, five Canadian provinces, and include more than 400 organizations. This program has announced the start of seven large-scale injection projects, with work beginning in FY08. Finally, the DOE leads the Carbon Sequestration Leadership Forum ([www.cslf.org](http://www.cslf.org)), which carries out technical exchanges and pursues capacity building efforts among the 21 member nations, including China.

CCS has the potential to substantially reduce US and global greenhouse gas emissions. On a technical basis, the potential is only limited by the characteristics of the geology, which must be capable of receiving large volumes of CO<sub>2</sub> rapidly and trapping it for long time spans. It appears that both the US and world have the potential to reduce global emissions between 15 and 55% by 2050 using CCS, based on current understandings of global geological options and energy supply infrastructure. The high reductions can be achieved through advanced technology options that connect the transportation sector to a decarbonized electric power sector which includes CCS (e.g., plug-in hybrid deployment, biofuels, or hydrogen). Importantly, this is a very attractive option for rapidly developing countries like China and India with large coal resources.

The estimated cost of most potential storage injection projects in the US ranges from \$1 to 12 per ton CO<sub>2</sub>; average cases range from \$5 to 8 per ton CO<sub>2</sub>. This is roughly 10% the total cost of capture and separation. The cost of monitoring and verification is much lower, with estimates from \$0.25 to 1.00 per ton CO<sub>2</sub>. The costs of assessment and site characterization are even less, estimated to be much less than \$0.001 per ton CO<sub>2</sub>.

**CCS Potential in China.** As previously mentioned, China is expected to surpass the United States in total CO<sub>2</sub> emissions in 2009, making it the largest emitter of greenhouse gases worldwide. Because the overwhelming majority of these emissions come from coal fired power plants, carbon capture and sequestration is an immensely important option for managing and reducing greenhouse emissions in China. Hence, an assessment of geological storage resources would be extremely valuable. It should provide several key pieces of technical information:

- A uniform, documented methodology that allows intercomparisons of geologic opportunities and accounts for the different trapping mechanisms.
- A capacity estimate for each region and for the nation as a whole.
- A relative ranking of potential sites by storage effectiveness and capacities.
- Information indicating the likely maximum sustainable injection rates.
- Data needed to develop economic models for GCS projects.

In short, national capacity assessments provide the same kinds of information that the national hydrocarbon assessments offer in mapping out the natural resources of the country with respect to this purpose. In this context, available pore volume to store CO<sub>2</sub> is such a resource.

In the US, the DOE's regional partnership program has just completed a Carbon Sequestration Atlas of North America, which serves as a preliminary capacity assessment for the continent. In Australia, the GEODISC program conducted a detailed assessment four years ago. That information, which was provided to businesses and government, has led to Australia's international leadership in GCS and buy-in from major industries such as coal mining and petroleum production. It also provided much information that entered into their regulatory framework, passed into law last month. GEODISC cost only \$10 million and took only 3 years.

The Australian government has begun a joint project with China to assess the most prospective basins in Eastern China for CO<sub>2</sub> storage. The Chinese Ministry of Science and Technology (MOST), PetroChina's research company (RIPED), and Geoscience Australia (their geological survey) have begun a survey of nine sedimentary basins previously identified as prospective. The Australian commitment to this project is A\$6M (~\$4.5M US) over three years. The information will help guide the selection of large-scale demonstration projects for CCS, and it will provide a basis for potential commercial abatement projects under Kyoto's clean development mechanism.

Because of the enormous scale required for commercial CCS operation, large projects are crucial to confirming our understanding of how CO<sub>2</sub> is trapped and stored, improving deployment operations, and demonstrating success. Smaller projects provide a partial learning platform; however, the key unresolved questions pertaining to commercial-scale injections can only be resolved at large scale. Many important hydrological, chemical, and mechanical responses only occur when operations reach thresholds that are not attainable by small-scale injections. For example, the pressure build-up could cause mechanical failure of the caprock, faults, or wells only when their yield strength is exceeded. That cannot be tested with small-scale injections. Similarly, the rock heterogeneities that control flow in target reservoirs do not become apparent until large volumes are injected for long periods of time.

These issues could be resolved by a select number of large-scale experimental projects (on the order of 1 million tons CO<sub>2</sub>/year injection) in reservoirs of different characteristics that are instrumented, monitored, and analyzed to verify the practical reliability and implementation of sequestration. Toward this end, China has shown interest in Integrated Gasification Combined Cycle (IGCC) plants with CCS. The Huaneng Group, a power producer based in Beijing, has pulled together a consortium of power and coal interests called GreenGen. Modeled after the US DOE FutureGen project, the GreenGen's goal is to build the first Chinese IGCC demo plant by 2010. Within the Carbon Sequestration Leadership Forum, China's Ministry of Commerce has partnered with the Canadian International Development Agency and the Alberta Research Council to investigate carbon storage and enhanced coal-bed methane recovery in deep coal seams. This \$10M project began in 2003, and an assessment well was completed in 2005. China might also be engaged in substantial (1 million ton or more) enhanced oil recovery projects using CO<sub>2</sub> from coal plants. These activities demonstrate a reasonable level of technical readiness.

Finally, there may be other opportunities to accelerate large-scale storage projects in China. Several researchers have identified large, pure CO<sub>2</sub> streams that are close to viable sequestration targets. These include hydrogen plants, chemical plants, fertilizer plants, and synthetic fuels

facilities. All of these sources come from coal feed stocks and gasification, providing a potential model for decarbonizing coal-plant emissions through CCS.

In summary, opportunities for rapid deployment of GCS exist in the US and China. There is enough technical knowledge to select a safe and effective storage site, plan a large-scale injection, monitor CO<sub>2</sub>, and remediate and mitigate any problems that might arise (e.g., well-bore leakage). This knowledge derives from over 100 years of groundwater resource work, oil and gas exploration and production, studies of geological analogs, natural gas storage site selection and operation, and hazardous waste disposal. A careful operator could begin work today at a commercial scale and confidently select and operate a site for 30 to 50 years. Widespread commercial deployment of CCS, however, poses additional technical challenges and concerns due to the scale of operations. An aggressive research, development, and deployment program could answer all the key technical questions within 10 years and could advise the formation of a legal and regulatory framework to protect the public without undue burden to industry.

Domestic projects for CCS are of the highest priority. Should funds beyond this allow, the US could pursue at least one large-scale carbon sequestration demonstration project in China. The project could be undertaken under the aegis of the Carbon Sequestration Leadership Forum together with the Asian-Pacific Partnership and be modeled after the Partnership program's Phase III projects. The effort could include participation by DOE/Fossil Energy, industry, and Chinese entities, and it could include US and Chinese universities, national laboratories, and the US State Department.

**Underground Coal Gasification (UCG).** UCG converts coal in-situ into a gaseous product, commonly known as synthesis gas or syngas. Through chemical reactions, gasification converts hydrocarbons at elevated pressures and temperatures into many potential products: chemical feedstock, liquid fuels, hydrogen, and syngas. The process provides numerous opportunities for pollution control, especially with respect to emissions of sulfur, nitrous oxides, and mercury. UCG could increase the available coal resource enormously by gasifying otherwise unmineable deep or thin coals in diverse geological settings. A 300-400% increase in recoverable coal reserves in the US is possible. For countries undergoing rapid economic expansion, including India and China, UCG may be a particularly compelling technology.

UCG has numerous advantages over conventional underground or strip mining and surface gasification, including:

- UCG eliminates conventional coal mining (and attendant safety issues such as mine collapse and asphyxiation), thereby reducing operating costs and surface damage;
- Coals that are unmineable (too deep, low grade, thin seams) can be exploited by UCG, thereby greatly increasing domestic resource availability;
- No surface gasification systems are needed, hence, capital costs are substantially reduced;
- No coal is transported at the surface, reducing cost, emissions, and local footprint associated with coal shipping and stockpiling;
- Most of the ash in the coal stays underground, thereby avoiding the need for excessive gas clean-up and the environmental issues associated with fly-ash waste storage;
- Some criteria pollutants (e.g., SO<sub>x</sub>, NO<sub>x</sub>) are not created and many other pollutants (mercury, particulates, sulfur species) are greatly reduced in volume and easier to handle;
- UCG requires far less energy to move to the surface both waste and usable product; and



- UCG produces less greenhouse gas than the combination of conventional mining and coal combustion (petroleum and coal combustion contribute two-thirds of US-produced carbon dioxide; coal mining by traditional methods contributes another greenhouse gas, methane, to the atmosphere). Furthermore, the UCG combustion cavity as well as adjacent strata can be used for subsequent geologic CO<sub>2</sub> sequestration operations, providing an added economic advantage over other clean coal technologies.

DOE will shortly release a report on Best Practices for Underground Coal Gasification. It summarizes the 20-year DOE research program in the 1970s and 1980s and discusses current national and international efforts. In addition, The President's Asian-Pacific Partnership program, led by the US State Department, has identified UCG as an important research area under the coal mining work group. Chinese representatives from government and industry attended an Asian Pacific Partnership meeting in Kolkata hosted by India's Ministry of Coal and US DOE.

UCG has been tested in many different experiments in many countries. The US carried out over 30 pilot projects between 1975 and 1996. The Soviet Union and successor states have conducted over 50 years of research on UCG, with field tests and several commercial projects, including an electric power plant in Angren, Uzbekistan that is still in operation after 47 years. Since 1991, China has executed at least 16 tests as well as several commercial UCG projects for chemical and fertilizer feedstocks. In 2000, Australia began a large pilot (Chinchilla) which produced syngas for 3 years before a controlled shut-down and controlled restart. At present, commercial projects are in various stages of development in the US, Canada, South Africa, India, Australia, New Zealand, and China to produce power, liquid fuels, and synthetic natural gas.

The economics of UCG appear extremely promising, which might help to accelerate its adoption. The capital expenses of UCG plants appear to be substantially less than the equivalent plant fed by surface gasifiers because purchase of a gasifier is not required. Similarly, operating expenses are likely to be much lower due to significantly reduced ash management facilities and the lack of coal mining and transportation costs. Even for plants requiring a substantial environmental monitoring program and additional swing facilities, UCG plants retain economic advantages.

**UCG in China.** The cost advantages may help to explain why China currently has the largest UCG program in the world, including 16 trials carried out since the late 1980s or now operating. These include the Xinhe #2 mine test, the industrial trial at Liuzhuang mine in Tangshan, XinWen's tests at Suncun in Shangdong, and the Caozhuang mine in Feicheng. The work uses abandoned galleries of coal mines for the gasification. Vertical boreholes are drilled into the gallery to act as the injection and production wells. A system of alternating air and steam injection is used to improve the production of hydrogen. The UCG center at the China University of Mining and Technology, Beijing, also is testing UCG in abandoned coal mines. A technical centre for UCG has been set up in the University of Beijing, which is exchanging technical information on UCG with the United Kingdom. Both laboratory and numerical projects are pursued, including a large autoclave to conduct experiments on large packed beds at elevated pressures and temperatures.

With government encouragement to diversify coal utilization, several Chinese companies are pursuing or utilizing UCG syngas. The XinWen coal mining group in Shangdong province has six reactors with syngas used for cooking and heating. A project in Shanxi Province uses UCG gas for the production of ammonia and hydrogen. Small-scale power production schemes using converted

coal boilers or gas turbines are also under consideration, as is a 350 MW electric generating plant. Finally, the XinAo Corporation has announced plans for a liquid fuel production facility fed by UCG, with methanol and dimethyl ether as likely products.

It would be highly beneficial for the US and China to collaborate on a joint demonstration program that would integrate UCG, hydrogen production, power production, and carbon sequestration—like the FutureGen and GreenGen programs. It would also be highly beneficial for the US to expand its UCG research program managed by the National Energy Technology Lab as part of the DOE Fossil Energy Program. Work should include technology development, geological assessment, and field demonstrations. As a component of this research, collaboration and technology exchanges with Chinese universities, national research centers, and companies would be beneficial.

## **VI. Closing**

Thank you for the opportunity to testify. I would like to make the following summary recommendations:

1. The US needs to continue to collaborate with China on climate research.
2. To understand better understand the global environmental effects of pollutants, increased support is needed for aerosol transport and emission verification research.
3. Clearly our highest priority should be to conduct domestic pilot projects for CCS. Should funds be available, it would be beneficial to also participate in a Chinese demonstration project. This could be as little effort as a technical exchange, or as much as a joint project.

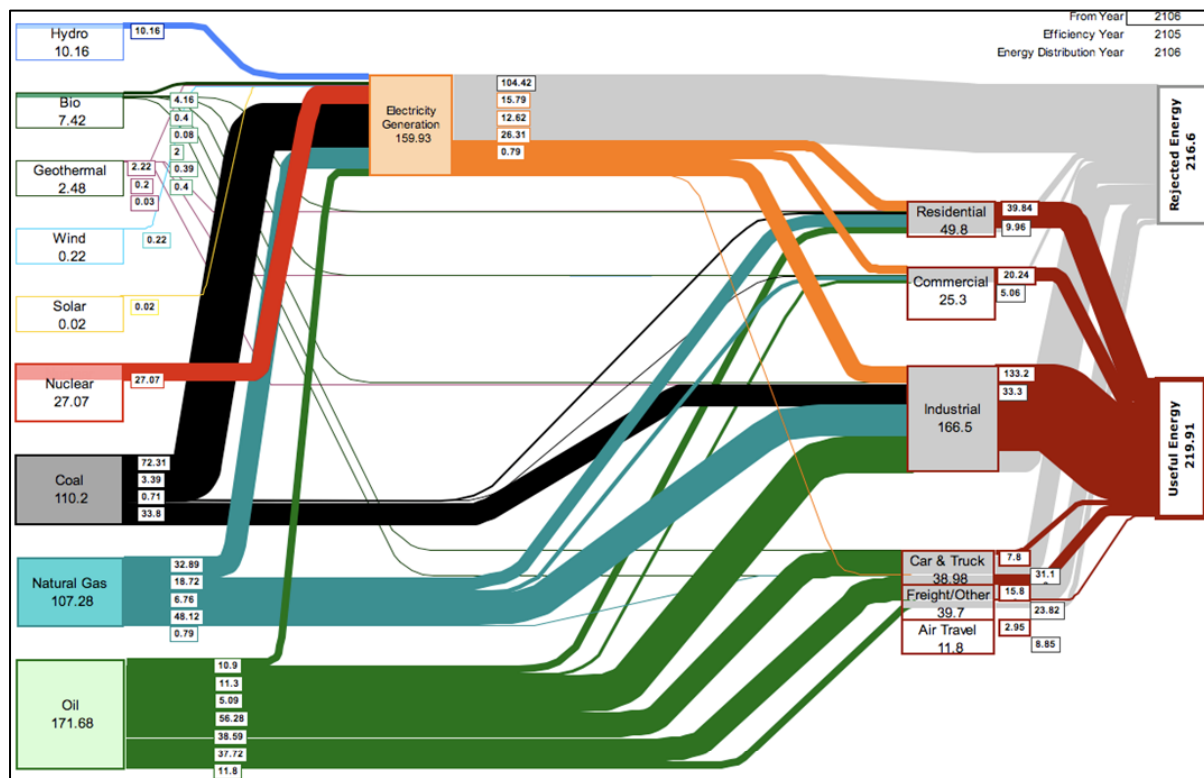


Figure 1. World energy: 435 Quads

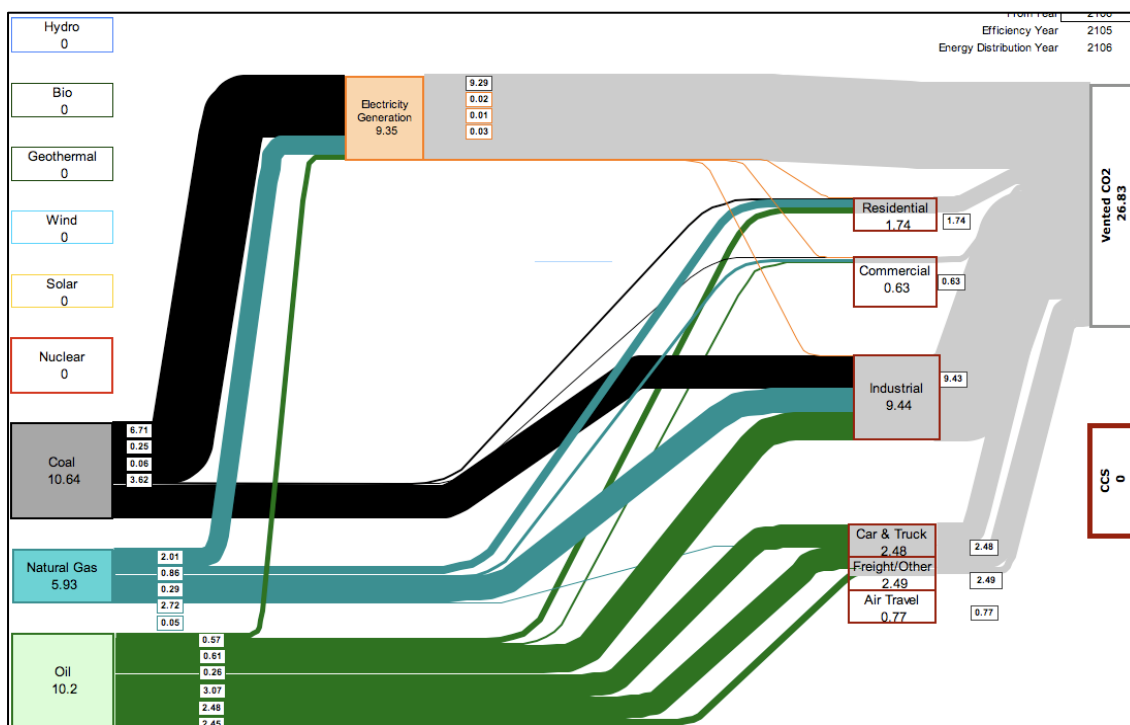


Figure 2 World carbon: 27 GtCO<sub>2</sub>/yr

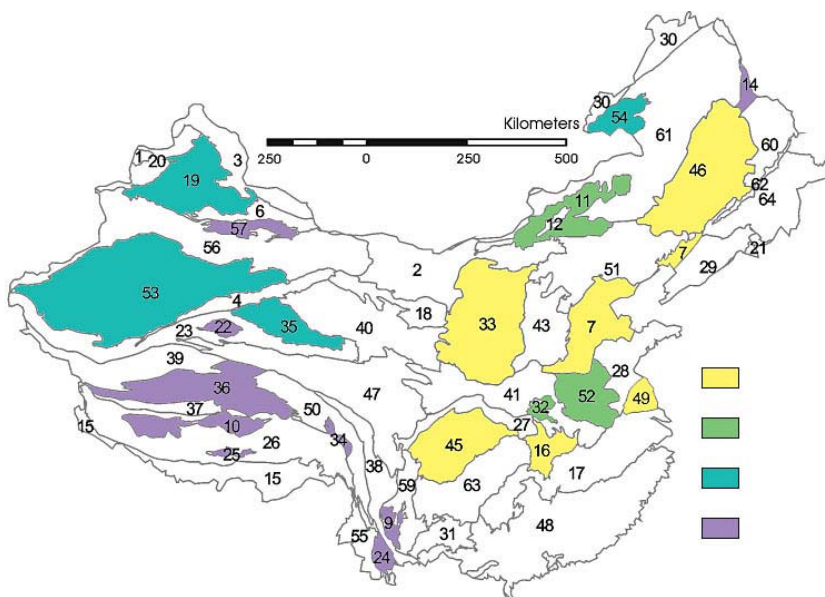
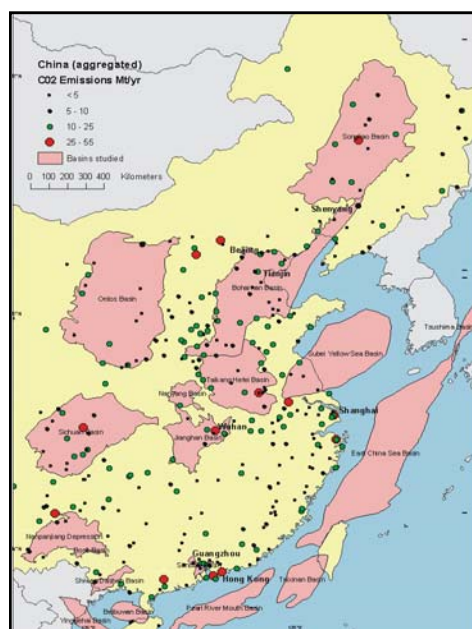


Figure 3: Tectonic map of onshore China; all colored areas are sedimentary basins. Yellow represent high priority for assessments; green represent second tier; blue represent third tier; fourth tier are purple. Ranking is based on closeness to CO<sub>2</sub> point sources, presence of hydrocarbons, and complexity of geology.



. Figure 4: East China onshore and offshore basins with annual CO<sub>2</sub> emissions.

## Key references

### Climate

- Buwen Dong; Cess, Robert D; Potter, Gerald L; Riyu Lu. "The 1997/98 El Nino: A test for climate models", *GEOPHYSICAL RESEARCH LETTERS*, VOL. 31, L12216, doi:10.1029/2004GL019956, 2004
- Zhang, Y, K. R. Sperber, and J. S. Boyle, 1997: Climatology and Interannual variation of East Asian winter monsoon: results from the 1979-1995 NCEP/NCAR reanalysis. UCRL-JC-125322, *Mon. Wea. Rev.*, 125, 2605-2619.
- Zhang, Y, K. R. Sperber, and J. S. Boyle, 1997: Interannual variation of East Asian winter monsoon and ENSO. UCRL-JC-124645R1, Proceedings of the Third Conference on East Asia and Western Pacific Meteorology and Climate.
- Zhang, Y, K. R. Sperber, J. S. Boyle, M. Dix, L. Ferranti, A. Kitoh, K.-M. Lau, D. Randall, L. Takacs, and R. Wetherald 1997: GCM simulated East Asian winter monsoon: Results from eight AMIP Models. *Clim. Dynam.*, 13, 796-820.

### Aerosol transport

- Atherton, C.S., S. Grotch, D.D. Parrish, J.E. Penner, and J.J. Walton, 1996a: The role of anthropogenic emissions of NO<sub>x</sub> on tropospheric ozone over the North Atlantic Ocean: A three dimensional, global model study, *Atmos. Env.*, **30**, 1739-1749.
- Atherton, C.S., S. Sillman, and J. Walton, 1996b: Three dimensional global modeling studies of the transport and photochemistry over the North Atlantic Ocean, *J. Geophys. Res.*, **101**, 29,289-29,304.
- Cameron-Smith, P., D. Bergmann, C. Chuang, S. Cliff, T. VanCuren, G. Bench, K. Perry, and P. Kelly, 2007: Trans-Pacific transport of aerosols dominates local sources over Northern California, review in process, *Science*.
- Chuang, C.C., J.E. Penner, K.E. Grant, J.M. Prospero, G.H. Rau, and K. Kawamoto, 2002: Cloud susceptibility and the first aerosol indirect forcing: Sensitivity to black carbon and aerosol concentrations, *J. Geophys. Res.*, **107**, 4564, doi:10.1029/2000JD00215.
- Chuang, C.C., J.E. Penner, K.E. Taylor, A.S. Grossman, and J.J. Walton, 1997: An assessment of the radiative effects of anthropogenic sulfate, *J. Geophys. Res.*, **102**, 3761-3778.
- Grant, K.E., C.C. Chuang, A.S. Grossman, and J.E. Penner, 1999: Modeling the spectral optical properties of ammonium sulfate and biomass burning aerosols; Parameterization of relative humidity effects and model results, *Atmos. Env.*, **33**, 2603-2620.
- Grant, K.E., A.S. Grossman, and R.L. Tarp, 1997: Methods and models used to parameterize the infrared absorption of methane and nitrous oxide for calculations within the LLNL/UCLA climate model, UCRL-ID-129290.
- Law, R.M., W. Peters, C. Rodenbeck, I. Baker, D.J. Bergmann, P. Bousquet, J. Brandt, L. Bruhwiler, P.J. Cameron-Smith, J.H. Christensen, F. Delage, A.S. Denning, S. Fan, C. Geels, S. Houweling, U. Karstens, S. R. Kawa, J. Kleist, M. Krol, S.-J. Lin, R. Lokupitiya, T. Maki, S. Maksyutov, Y. Niwa, R. Onishi, N. Parazoo, P.K. Patra, G. Pieterse, M. Satoh, S. Serrar, S. Taguchi, M. Takigawa, A.T. Vermeulen, Z. Zhu, et al., 2007: TransCom model simulations of hourly CO<sub>2</sub>: Experimental overview and diurnal cycle results for 2002, manuscript in preparation, *J. Geophys. Res.*
- Penner, J.E., C.S. Atherton, J. Dignon, S.J. Ghan, J.J. Walton, and S. Hameed, 1991: Tropospheric nitrogen: A three-dimensional study of sources, distributions, and deposition. *J. Geophys. Res.*, **96**, 959-990.
- Rotman, D.A., C.S. Atherton, D.J. Bergmann, P.J. Cameron-Smith, C.C. Chuang, P.S. Connell, J.E. Dignon, A. Franz, K.E. Grant, D.E. Kinnison, C.R. Molenkamp, D.D. Proctor, J.R. Tannahill, 2004: IMPACT, the LLNL 3D global atmospheric chemical transport model for

the combined troposphere and stratosphere: Model description and analysis of ozone and other trace gases, *J. Geophys. Res.*, **109** doi:10.1029/2002JD003155.  
Zhang, K.M. and A.S. Wexler, 2002: Modeling the number distributions of urban and regional aerosols: Theoretical foundations, *Atmos. Env.*, **36**, 1863-1874.

### **Carbon Sequestration**

Benson SM, Cook P, 2005, Chapter 5: Underground Geological Storage, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, [www.ipcc.ch](http://www.ipcc.ch) , pp. 5-1 to 5-134

MIT, 2007, Future of Coal in a Carbon Constrained World, MIT Press

US DOE, 2007, Carbon Sequestration Technology Roadmap and Program Plan for 2007, Morgantown, WV, 39p.

IPCC, 2005, Summary for Policy Makers, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, [www.ipcc.ch](http://www.ipcc.ch)

Jarrell PM, Fox CE, Stein MH, Webb SL, 2002, Practical aspects of CO<sub>2</sub> flooding. Monograph 22. Society of Petroleum Engineers, Richardson, TX, USA.

### **Capacity Assessments**

Bradshaw J, Allison G, Bradshaw BE, Nguyen V, Rigg AJ, Spencer L, Wilson, P., Australia's CO<sub>2</sub> Geological storage potential and matching of emission sources to potential sinks. In: Greenhouse gas control technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1–4 October 2002, Kyoto, 2003

Carbon Sequestration Leadership Forum, Discussion Paper on Capacity Estimation, Technical Working Group, Olveida, Spain, 2005. <http://www.cslforum.org/presentations.htm>

Friedmann, S.J., Dooley, J.J., Held, H., Edenhofer, O., The low cost of geological assessment for underground CO<sub>2</sub> storage: Policy and economic implications, *Energy Conversion Management*, in press

US Department of Energy, Carbon Sequestration Atlas for the United States and Canada, Department of Energy, Office of Fossil Energy, National Energy Technology Lab, Morgantown, WV, 90p. [http://www.netl.doe.gov/publications/carbon\\_seq/atlas/index.html](http://www.netl.doe.gov/publications/carbon_seq/atlas/index.html)

### **Underground Coal Gasification**

US Department of Energy, Best Practices in Underground Coal Gasification, Department of Energy, Office of Fossil Energy, DOE Report number pending, 119 p.

Blinderman, M.S., and Friedmann, S.J., 2006, Underground Coal Gasification with Carbon Capture and Storage: A Pathway to a Low-Cost, Low-Carbon Gas for Power Generation and Chemical Syntheses, NETL 5<sup>th</sup>